

**Final Report
for
NASA Grant NAG5-4615
“Satellite Atmosphere and
Io Torus Observations”**

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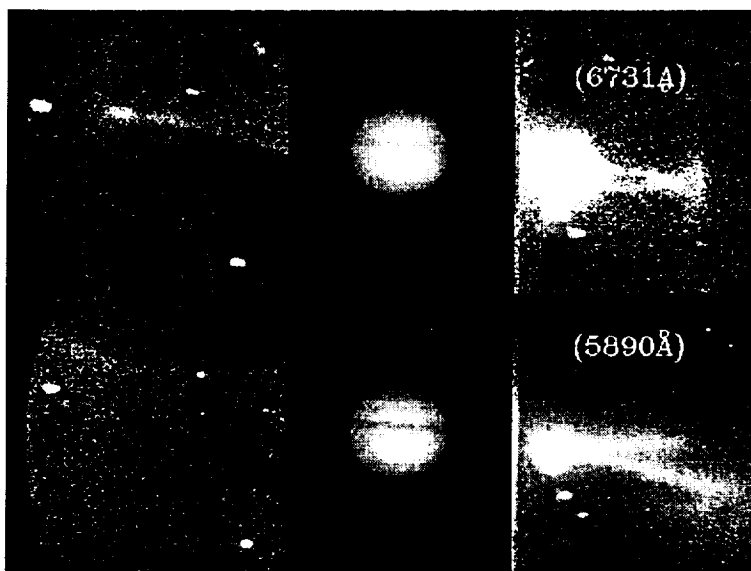
Abstract

This document is the final report for NASA Grant NAG5-4615, "Satellite Atmosphere and Io Torus Observations", Nicholas M. Schneider, P.I., awarded to the University of Colorado, 5/15/97-5/14/00.

Overview

Io is the most volcanically active body in the solar system, and it is embedded deep within the strongest magnetosphere of any planet. This combination of circumstances leads to a host of scientifically compelling phenomena, including (1) an atmosphere out of proportion with such a small object, (2) a correspondingly large atmospheric escape rate, (3) a ring of dense plasma locked in a feedback loop with the atmosphere, and (4) a host of Io-induced emissions from radio bursts to UV auroral spots on Jupiter. This proposal seeks to continue our investigation into the physics connecting these phenomena, with emphasis on Io's atmosphere and plasma torus. The physical processes are clearly of interest for Io, and also other places in the solar system where they are important but not so readily observable.

Figure 1: Groundbased images of Io's escaping atmosphere (bottom) and the resulting torus of plasma encircling Jupiter (top). The bottom image shows neutral sodium; the appearance of the cloud reflects the many processes which cause atmospheric escape. The top image shows S^+ ; the structure reveals the combined effects of mass and energy supply. The ring is tilted due to the tilt of Jupiter's magnetic field. These observations were made in collaboration with J.T. Trauger during a previous funding cycle for our program.



Twenty-five years of groundbased observations and a handful of interplanetary and Earth-orbiting spacecraft have given an adequate general picture of Io's atmosphere and torus (reviewed by Spencer & Schneider 1996). Io's volcanism pumps sulfur dioxide and other species onto the surface and into its atmosphere. These materials escape Io's weak gravity by several mechanisms and form extended "neutral clouds" around Io orbit (Figure 1, bottom). The atoms and molecules are ionized by the plasma, and are swept into a ring by Jupiter's rapidly rotating magnetic field (Figure 1, top). The plasma, along with its

concomitant electric and magnetic fields has a remarkably strong interaction with Io, leading to a variety of excitation and escape processes in Io's atmosphere. Thus the torus and atmosphere form a tightly coupled system which must be studied as a whole.

Major questions have been raised by recent work, including Galileo observations. We will discuss some of the major issues "from the ground up". We summarize these fundamental problems with the following questions. While we are not suggesting that we can resolve all the above issues, we have identified critical observations we can make that offer significant progress in each area:

- What role does chlorine play in Io's chemistry? Is it related to sodium?
- Why does Io's atmosphere emit visible radiation? What species are involved?
- How and why do Io's atmospheric escape processes vary?
- What process powers Io torus emissions? How does it control torus structure and brightness?

It might seem that these fundamental questions would be best answered by spacecraft, and that groundbased observations of Io's atmosphere and torus would be obsolete. Galileo will fly through the torus - and atmosphere - in a few months; Cassini, with superior instrumentation (and data rate) is on its way, and HST is now capable of spectral imaging from UV through visible wavelengths with STIS. But each of these spacecraft has severe limitations - be it resolution, temporal or spatial coverage, or finite resources split among many interests. Groundbased observations can (1) fill in key gaps in spacecraft capabilities; (2) offer specialized capabilities developed to answer specific questions; (3) continue to provide new discoveries long after interplanetary missions are over. We will draw attention to these advantages in the tasks below.

Summary of Results from NAG5-4615

Io Chemistry. Our most exciting result is the serendipitous discovery of chlorine in the Io plasma torus (Figure 2). While Cl^+ is only a minor ingredient in the torus and has little overall effect there, it must originate on Io. Previously, only Iogenic S, O, Na, K (and possibly H) were seen, and the relative purity of the system continues to baffle Io researchers. The figure shows the clear detection of the Cl^+ forbidden line at 8579\AA with the same spectral and spatial characteristics as all of the other torus emissions. This is the first new species detected in the torus in two decades; this wavelength range had apparently never been searched with CCD technology. Cl^+ is a minor species in the torus (~1%), but will force a major rethinking of Io chemistry. It raises some fundamental questions about the origin of Io's atmosphere, particularly the volcano-surface-atmosphere connections, and subsequent atmospheric chemistry. For example, is Cl supplied from NaCl, implying a non-silicate origin of Na? Or is Cl emitted directly from volcanoes, as on Earth? Does Cl play as important a role in Io atmospheric chemistry as it does in Earth's? Preliminary results have been published in GRL (Kueppers & Schneider 2000). [Postdoc Kueppers was supported by this grant, but has recently

returned to Europe for a new position.] Previously, only Iogenic S, O, Na, K (and possibly H) were seen, and the relative purity

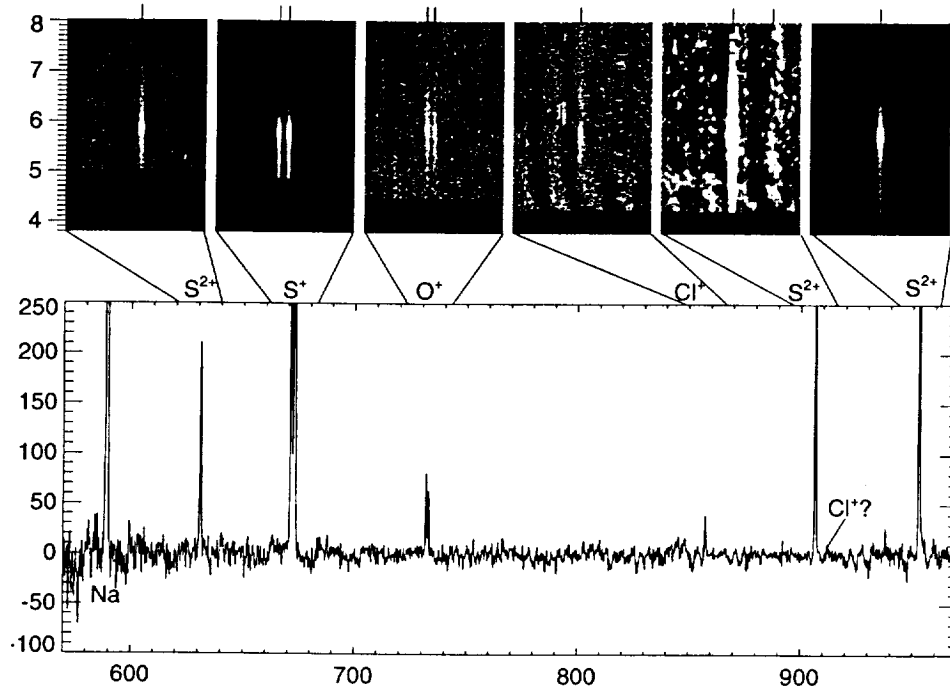


Figure 2: Sample 20-minute torus spectrum from the KPNO 2.1m+GoldCam, showing 10 emission lines from five species. (Neutral potassium would also have been readily detectable if Io had not been on the opposite side of Jupiter.) The bottom section shows the spectrum plotted in nm. The top panels show expanded version of the ion lines; the vertical axis is R_j from Jupiter. The first detection of the O^+ doublet at 7319,7330Å is unambiguous in panel 3. The discovery of chlorine is evident in the fourth panel; a second chlorine feature is marginal in the fifth panel to the right of the bright line. CCD fringeing is also apparent in these panels. Small ticks indicate the predicted wavelengths of the lines. Line ratios can be used to constrain electron density and temperature. The ability to obtain such a rich spectrum so efficiently from the ground is unprecedented.

Atmospheric Escape. Escape on Io is mostly directly observable through sodium observations. Our observations of high-speed escape from Io have identified a new escape process: ionospheric loss driven by the electrodynamic interaction of Io with Jupiter's magnetosphere. This result stems from Wilson's thesis work under this grant; it has been accepted for publication in JGR-Planets (Wilson & Schneider 1999). Furthermore, long-term observations supported by the current grant have paid off in identifying a "dual nature" of Io's sodium cloud. Atmospheric loss is sometimes dominated by the high-speed escape as described above. At other times, escape is dominated by the brute force impact of plasma on the atmosphere, resulting in slower escape. This result arose from the collaboration with Mendillo and Wilson at Boston University, and was made possible by combining their large-scale observations and our close-up images of the sodium cloud.

Those results have been submitted to Icarus (Wilson, Mendillo, Baumgardner, Schneider and Trauger 1999).

Finally, we have gotten our first close-up look at the ionospheric escape process with Galileo (figure 2 below). It matches all predictions from the Wilson & Schneider mechanism. Furthermore, the image shows that escape is confined to an area much smaller than Io's diameter, indicating that the ionosphere is restricted to low latitudes. This result (the work of graduate student Burger under this grant, before JSDAP funds were available) has been submitted to Science (Burger & Schneider 1999).

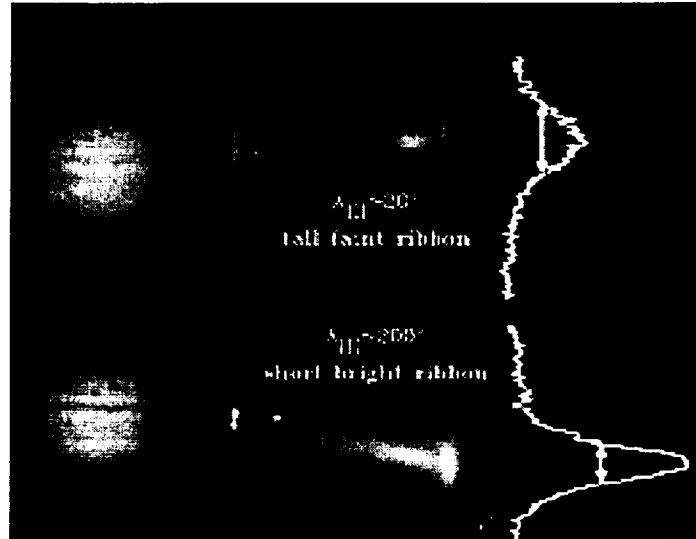
Figure 3: Galileo images of the "directional feature" (Pilcher et al. 1984, Goldberg et al. 1984), recently demonstrated to arise from ionospheric escape driven by currents. The "jet" projecting down and to the right is generated by the partial neutralization of ionospheric currents driving sodium atoms out of Io's atmosphere. Top image through clear filter, bottom image through green. Note that the jet is perpendicular to the local Jupiter field line (drawn in black), indicating that Jupiter's magnetic field dominates any from Io. The width of the jet is much less than an Io diameter. (From Burger & Schneider 1999.)



Torus Structure and Energetics. Our thorough observations of the S^+ torus yielded the best 3-d description of the torus brightness and structure (Schneider and Trauger 1995, supported by previous Planetary Astronomy funding). For example, we answered the 20-year-old question of what property of the torus is responsible for making half of the torus up to four times brighter than the other. We showed it can be attributed to a vertical compression of plasma on one side (from lower ion temperatures) resulting in higher emission rates (Figure 5 below). In the current cycle we moved forward in seeking for insights onto the mechanism causing this asymmetry. We mined the existing dataset for clues, and discovered that the large difference in ion temperatures offers a natural tests of energy supply theories. The observations and accompanying theory were published in Schneider et al. 1997. Based on the new theory, we made simultaneous observations with Galileo, HST, EUVE and Mt. Wilson. The large scope of the project has make progress slow, but the results will be submitted by July (Schneider, Kueppers, McGrath, Trauger, Hall, in preparation)..

In general, observations of torus structure (density, temperature, composition, etc.) ultimately lead to insights on the processes which form the torus. For example, Volwerk et al. 1997 suggested that densities were 5-10 \times higher than our view; this would have substantially altered torus energy supply theories. We refuted their claims in Kueppers & Schneider 1997.

Figure 4: Two images of the torus west ansa taken half a Jupiter rotation apart, sampling opposite sides of the torus. The bottom image is brighter because the plasma is confined to a smaller volume (vertically), as the intensity traces show. Vertical extent is directly related to ion temperature: hotter ions move farther from the equator. (From Schneider et al. 1997).



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